

NUMERICAL EVALUATION OF SURFACE MODIFICATIONS AT LANDING SITE DUE TO SPACECRAFT (SOFT) LANDING ON THE MOON

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Abstract:

Understanding surface modifications at landing site during spacecraft landing on planetary surfaces is important for planetary missions from scientific as well as engineering perspectives. An attempt has been made in this work to numerically investigate the disturbance caused to the lunar surface during soft landing. The variability of eject velocity of dust, eject mass flux rate, ejecta amount etc. has been studied. The effect of lander hovering time and hovering altitude on the extent of disturbance is also evaluated. The study thus carried out will help us in understanding the surface modifications during landing thereby making it easier to plan a descent trajectory that minimizes the extent of disturbance. The information about the extent of damage will also be helpful in interpreting the data obtained from experiments carried on the lunar surface in vicinity of the lander.

Keywords: soil disturbance, surface modification, soft landing; hovering, jet plume, descent trajectory.

1. Introduction: Understanding surface modifications at landing site during spacecraft landing on planetary surfaces is important for planetary missions from scientific as well as engineering perspectives. In situ experiments that aim to investigate the lunar surface near the landing site require a pristine lunar surface to derive meaningful science. Heat flow experiments that estimate heat flow in and out of the lunar surface make use of the upper few cm of the fluffy layer to derive the thermo-physical behavior of the lunar surface and subsurface [1]. The planned future lunar missions carry instruments aimed at carrying out in situ investigation of the thermal behavior of the Moon. Additionally, the geological experiments that analyze the local (w.r.t. the lander/rover) samples such as those planned on Chandrayaan-2 rover [2] require minimum disturbance to the lunar surface. Even if the damage to the surface is inevitable, a prior knowledge of the extent to which the damage can occur will help arrive at better interpretation of results from the corresponding experiment data by incorporating the resulting surface disturbances in their respective derivations/models. From mission planning perspective, the blown out dust might affect the optical instruments on board the lander or rover. The solar panel efficiency can also degrade if the lofted dust particles falls on the panels [3]. A properly planned descent trajectory may minimize these damages largely.

Bulk properties of the landing site, especially the upper layer of its regolith and its physical interaction with the supersonic jet plumes principally determines the possible modifications to the surface. The resulted cratering and consequently ejected particle kinematics provide clues to the physical affects that might have caused to its surroundings. Only successful lunar soft landings were those of Surveyor, Luna and Apollo missions that were carried out nearly 4 decades ago until the recent landing of Chang'e 3 mission [4]. India's second mission to Moon, Chandrayaan-2, also plans to land on lunar surface. Several such missions might also

follow in near future. In this context, understanding the disturbance caused to the surface due to spacecraft landings gains prominence. Therefore, an effort has been made to numerically investigate the plume/soil dynamics and effects of jet impingement on the lunar surface and some results from the work are presented in this paper.

2. Fundamentals of jet cratering during lunar landings

Fig. 1 shows a schematic of interaction of the jet plume with the lunar surface. Plume-soil interaction can be seen as an energy transfer phenomenon where the energy contained in the jet particles is transferred in part to the soil particles and rest is dissipated as heat and in inter-particle collisions. As shown in Fig. 1 (not to scale), the rocket exhaust plume coming out of the nozzle exit strikes the lunar surface with an impingement pressure. This pressure is dependent on the jet expansion ratio (e), a parameter that can be defined as the ratio of exhaust plume pressure at the nozzle exit plane to that in the ambient planetary atmosphere at surface level [5]. This plume strikes the planetary surface resulting in a shear force at the boundary of the plume and the soil. The shear stress of the plume is countered by the shear strength of the soil/surface. When the shear stress caused by the plume exceeds the shear strength of the soil, the particles are rolled away from their position before being ejected into the lunar atmosphere. The momentum carried by the diffused gases is transferred partly to the ejected particles. This results in divot/crater formation on the planetary surface.

The problem of jet cratering was a topic of great interest during the Apollo and Viking missions. Many theories were developed during those periods of time. Some of these theories discussed about the possible mechanisms of cratering. The theories developed during the Apollo and Viking programs predicted three types of cratering mechanisms. One of the mechanisms is

Viscous erosion, in which the grains of the upper layers of the regolith are subjected to uneven force due to the dynamic pressure exerted by the jet plume. This unbalanced force exerts torque and the regolith/soil particles are ejected out to their surroundings. Roberts L. [6] developed this theory in the 1960s. This theory was studied for the case of Moon by Land and Clark [7] and Hutton [8]. *Bearing capacity failure* is another cratering mechanism which is the mechanical pushing of the soil/surface. To give an equivalent example, when we stand on the sandy surface of the beach and apply gradual pressure with our feet, it forms a foot-shaped hole when it can no longer bear the load of our weight. It undergoes bearing capacity failure, resulting in mechanical pushing of the entire surface. Similarly, in case of jet-soil interface, it occurs when the pressure under the jet becomes larger than the bearing capacity of the soil surface. Alexander et. Al. [9] studied this theory and it has not occurred on Moon so far because of the larger bulk density of the lunar regolith. *Diffused gas eruption*, the third mechanism of cratering, occurs when the gaseous constituents of the jet enter into the pore spaces of the soil and come out at some other location or time bringing soil grains along with them. This mechanism was studied by Scott and Ko [10].

Metzger et al (2008) modified Robert's erosion theory in several ways [11]. First modification to Roberts' theory was to impose the ejection angles as measured in the Apollo landing videos [12] which showed that most of the ejected particles had an ejection angle of less than 3° . Second modification was integration of Roberts' equations over the lunar particle size distribution. Particle size distributions obtained using the JSC-1A lunar soil simulant were used to arrive at the particle (dn/dt), no. of particle of given diameter per unit time. Third modification that they

made was addition of a material damage model that predicts the number and size of divots that the impinging particles will cause to their surroundings.

Metzger et al in their other paper [13] demonstrated the pit formation due to high velocity exhaust plumes experimentally. Morris et al [14] made an elaborative effort to investigate the plume flow fields and the cratering mechanisms caused by jet impingement. Loosely coupled continuum Direct Simulation Monte Carlo (DSMC) solver- a method that employs probabilistic simulation to solve the Boltzmann transport equation for a fluid with finite Knudsen number- were used to simulate the interaction between the exhaust from a rocket engine with the lunar surface. Both the dust trajectories and the flow fields were computed for various hovering altitudes and dust grain sizes. These studies provide us with some understanding of jet induced cratering on Moon. In the next section, we shall discuss the further developments and present the work done to quantitatively understand the jet cratering during lunar landings.

3. Methodology: Most of the studies carried out so far focus on dust particle flow field and trajectories. In this work, we set out with a different objective since we needed to estimate the extent of damage and the area/volume affected by cratering in order to better interpret the scientific outcome of in situ experiments being conducted near the affected area. From the present study, we understand the pit formation and derived its dimensions as a function of average grain size and hardness of the dust particles. Additionally, we have also evaluated the ejected dust velocities and mass flux densities to meet our objective.

The methodology consists of the following steps. First the eject particle velocities are calculated as a function of various parameters appearing in equations (3), (4) and (5). The mass

flux rate is calculated using the Robert's theory, i.e. equation (2). The material damage model based on Sheldon-Kanhare equation [15] was applied to obtain the crater dimensions. The material damage model has been applied for calculating the damage done by the ejected dust particles to the surrounding solid surfaces. Here, the same damage model was used for evaluating the damage done to the lunar surface by the impinging jet particles. The volume of pit caused by the impinging particles is calculated using equation (1).

$$V = K_D v^3 D^3 \sigma^{3/2} H_v^{-3/2} \quad (1)$$

The most dominant parameter here is the impinging particle velocity and the dust grain size. As Metzger et al have shown [11] that, for JSC-1A lunar simulant sample, the probability distribution of particle dimensions peaks near 10 micron, we restricted our study to particle dimensions varying from 1 to 100 microns. For cases where a constant grain size was required, it was assumed 10 micron since this value is most representative of the upper fluffy layer of the lunar surface [1]. The following set of equations, all given by Robert's in his theory, was used for the calculations.

$$\frac{dm}{dt} = 2 \frac{(\tau - \tau_c)}{a \cdot u} \quad (2)$$

where

$$a = \left[0.5 + \sqrt{\left(\frac{0.25\varepsilon + 1}{\varepsilon} \right)} \right]^{-1} \quad (3)$$

and

$$\varepsilon = k \left[\frac{1}{D^2} + \frac{1}{D} \left(\frac{(4 + k_h) C_d F}{72 e \sqrt{RT_c} \mu_c h^2} \right) \right] \quad (4)$$

and

$$k = \frac{18 \mu_c h}{\sigma R T_c (4 + k_h)} \quad (5)$$

and

$$k_h = \gamma(\gamma - 1) M_n^2 \quad (6)$$

$\frac{dm}{dt}$ is the mass flux rate per unit area of the ejected dust particles. τ is the shear stress caused by the impinging jet plume on the surface of moon. τ_c is the shear strength of the soil is given by the equation (7). The two components of the shear strength are the cohesive strength (c) of the soil (between the individual grains) and the resistive strength arising due to the frictional force between the layers which is a function of pressure P exerted by the plume and the friction angle ϕ of the soil. Friction angle is equivalent to the dynamic friction coefficient of the soil.

$$\tau_c = c + P \tan(\phi) \quad (7)$$

c is the cohesive stress of the soil. u is the average velocity of the impinging particles. a is the fraction of the impinging particle velocity imparted to the soil particles. D and C_d are the diameter and drag coefficient of dust particles. F and h are the engine thrust and hovering height, respectively. T_c and μ_c are the combustion chamber temperature and viscosity, respectively. k_h is the hypersonic factor, a function of ratio of specific heats (γ) and Mach number (M_n) of the jet at the exit plane of the nozzle.

4. Sensitivity study of the parameters:

Table 1 lists the parameters and their nominal values used for calculations. For each case, all combinations of parameter variation were used for calculations to see which parameters are more dominant. There were a number of parameters affecting each physical quantity like mass flux rate and eject velocity, but not all of may be significant. Also, the ground parameters such as soil bulk density, grain size, cohesive force between grains etc. are less likely to vary significantly from mission to mission at a given location compared to the spacecraft side parameters. Keeping this in mind, finally four parameters were chosen for this study, which we considered as the most influential ones. These are the eject velocity (v), grain size of the soil particles (D), the hovering

height (h) of the lander and hovering duration (t). Hovering time affects the overall damage done to the surface as the time derivative quantities like mass flux rate etc. are integrated over the hovering time duration to obtain the full damage over that duration. Ground parameters like drag coefficient and friction angle were less significant. Typical values of engine parameters viz. engine thrust, nozzle diameter etc. were used. The material parameters such as particle density, diameter, cohesive strength etc. were taken from Lunar Sourcebook [16].

While using the material damage model for calculating the total volume of the crater, the dominant factor was the hovering height and time. The Vicker's hardness of lunar surface was taken to be around 100-600 [17].

5. Results and Discussion:

Four different cases of parameter variability, as shown in table 2. Three values were chosen in each case with the typical value sandwiched between the typical maximum and minimum values. For example, in case 1, the soil bulk density assumed three values- 1.5 g/cc, 1 g/cc and 0.5 g/cc. Case 2 has variation of hovering duration of the lander, i.e. the time duration for which the thrusters of the lander fire at a given location. In the third case, the impact velocity of the jet plumes varies from a maximum of 3,500 m/s to a minimum of 15,00 m/s. In the 4th case, the hovering altitude varies between 15 m to 5m. The obtained results are presented in following paragraphs.

5.1 Effect of hovering time:

In case 2, the hovering duration of the lander is varied. The hovering duration is the most dominant factor in determining the amount of damage done to the surface. It is because the incoming jet plume particles interact with the soil particles and neither the plume nor the ejected

particle has any effect on the dynamics of the interaction, as if they did not exist. This implies a proportional relationship between the time duration over which the plume is active to the amount of dust ejected. As shown in Fig. 2, the ejected mass increases almost 3 times as the hovering duration is increased from 25 seconds to 45 seconds. The variation is plotted with respect to the soil's Vicker's hardness which is variable on Moon and can range from 50 to up to 1000. All the other parameter values were as listed in table 1. The hovering altitude is assumed to be 5 m.

5.2 Effect of hovering altitude:

In fig. 3, we observe that the mass flux rate is different for different hovering altitude. This is a direct result of Robert's equation. One interesting corollary of this phenomenon is that, for a conical plume profile, the footprint of the plume changes as the hovering altitude changes resulting in the disturbance getting distributed over larger area for higher altitudes. That is, for a higher altitude, the same amount of regolith mass is ejected from a larger surface area which is translated into lesser depth of disturbance. For experiments that are sensitive to the upper few cm of layer such as the heatflow experiments, the depth of layer through which the disturbance penetrates is extremely important. Therefore, a properly planned descent trajectory in which most of the firing of thruster is done at higher altitudes will be better in terms of successfully achieving the experiment objectives.

5.3 Effect of average velocity of plume particles/agglomerates:

Fig. 4 shows the variation of eject particle velocity with grain size keeping the soil density at 1.5 g/cc. The altitude of the lander is varied from 5 m to 100 m. All other parameters had nominal values as listed in Table 1. As the altitude is increased, the ejected particles gain lesser velocity. The eject velocities are almost same as the impinging plume velocity until 10 micron

grain size. After this, the velocity decreases rapidly with grain size and reaches a saturation level for mm range particles. Since most of the particles of the regolith fall in the 1-100 micron range, an average velocity of at least around 2000 m/s can be expected.

5.4 Effect of average velocity of plume particles/agglomerates:

The average plume velocity influences the volume of the crater formed during the landing. It is shown in Fig. 5. The plume velocity is a function of engine parameters such as engine thrust, chamber pressure, temperature etc. The volume of the crater is calculated based on the material damage model of Sheldon-Kanhare. Here, we assumed the plume to be constituted of particles of diameters in sub-micron range and with a bulk density of about 0.011 [16]. With these parameters and applying the Sheldon-Kanhare equation, we found the volume of the crater formed by a single plume particle/agglomerate. The number of such divots is calculated by multiplying this volume by n , the number of particles impinging per unit time per unit area. The overall volume of the crater increases to up to 25 to 30 times as the average plume velocity varies from 1500 m/s to 3500 m/s. This overall eject volume is also dependent on the hovering duration and altitude which have been kept constant here.

5.5 Effect of bulk soil density:

In case 1, the soil bulk density was varied around the typical soil density on lunar surface. 1.5 g/cc represents the region of high grain size soil. Rock presence in the regolith can increase the bulk density from the nominal to this level. The nominal value of 1 g/cc is chosen since the average density of JSC-1A samples was found to be around 1.1 g/cc [16]. In case of presence of highly fluffy layer, the bulk density can drop as low as 0.5 g/cc which is chosen as the third

value of the density. All the other parameters whichever applicable were same as listed in Table 1. The hovering height and duration are taken as 5 m and 30 s respectively. The figure 6 shows that the mass flux rate is proportional to density of the soil. Its effect is invisible for particles in sub-micron range but as the particle size increases beyond 40-50 micron, we see an increase in ejected mass flux rate. From the first principle we expect the curve to reach saturation and then start monotonically decreasing as the gravitation pull overtakes the kinetic energy of the particles. As it was showed by Metzger et al [11] that majority of the particles in JSC-1A were in the range of 10-100 microns, it can be concluded that grain size has little effect on mass flux rate barring cases where the higher grain sizes are in abundance.

Mass flux rate variation with grain size for different soil densities is shown in figure 6. The bulk density dependence of the mass flux rate is insignificant for grain sizes less than 10 microns. For grain sizes more than 10 microns, the mass flux rate increases exponentially with grain size and is proportional to the bulk density of the soil. As the grain size grows large, the mass flux rate should decrease because of the counter attack of gravitational pull on particles but this effect is not visible in the plot because Robert's theory does not hold good at higher grain sizes. Also, for extreme low grain sizes, say less than 1 micron, the cohesive force between the particles is much stronger resulting in a decrease in Mass flux rate. But since the cohesive stress of the soil is kept constant throughout, this effect is not seen in the plot of fig. 6.

Based on the kinematics of the ejected dust particle, we obtained the maximum horizontal range a particle can achieve, maximum time duration for which a particle can remain suspended in lunar atmosphere and the maximum height a particle can achieve. An illustration of the particle ejection is shown in Fig. 7. The figure is not to scale. A conical plume flow field is shown in the figure and the lander is assumed to be landing vertically downwards. The exhaust plumes will

drift the dust particles in horizontal direction. This means the probability of a dust particle getting ejected at higher angles is lesser. Dust particles are assumed to be spherical and their dimensions are exaggerated.

The results show that, more the hovering time more the volume of dust ejected. The hovering height and the nozzle axis orientation with respect to the lunar surface normal affect the damaged area. Since the Moon does not have an atmosphere and the nozzle in our study is assumed cylindrical, the hovering height has a negligible effect on the volume of the dust lofted because it is assumed that all the particles coming out of the nozzle reach the surface without interacting with each other. However, the volume is affected by the hovering time. Therefore, at a given hovering altitude, the longer the engine remain ON, the more damage in terms of volume is done to the surface. Since the plume profile is conical in nature, the disturbed area will increase as hovering height is increased. This implies that for minimum damage to the surface, hovering time should decrease as hovering altitude is lowered. Hovering time at lower altitudes, especially below 5 m should be kept minimum. Also, by properly planning a descent trajectory, the disturbance can be spread over a larger area resulting in very small damage (a few mm) at or near the landing site. A vertical landing should be avoided as long as possible.

6. Summary and Future Work: The lunar landings planned in future and the preparations of various nations and space agencies for such landings require a properly planned mission to deliver the best possible opportunities to onboard experiments. Especially in case of experiments demanding minimum disturbance to the surface, this problem becomes significant. In this paper, we have attempted to understand the extent of damage done to the surface and the variability of many important physical quantities using numerical techniques. The most crucial part is the

landing descent trajectory. Optimum trajectory will be the one that minimizes the hovering period at lower altitudes and the thruster orientation w.r.t. the surface normal. It is understood that the braking should start from high altitudes and should be stopped/minimized as it reaches within 10 m of the lunar surface. Since the problem considered in this work is quite complicated to solve from first principles, a lot of assumptions were made to simplify the mathematics involved. In future, a more elaborate attempt with lesser assumptions and with more accurate parameter values is planned to be carried out in order to refine our understanding of this subject further.

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Table Caption

Table 1: List of parameters and their typical values used in the investigation.

Table 2: List of all the dominant parameters and their variation limits.

Image Caption

Figure 1: Illustration of plume-surface interaction (not to scale. Just for representation purpose only. Particle dimensions are exaggerated)

Figure 2: Plot showing variation of ejected regolith mass as a function of surface hardness for varying hovering durations.

Figure 3. Plot of mass flux rate as a function of grain size for different hovering altitudes.

Figure 4: Velocity of the ejected particle as a function of their grain size for hovering altitudes of 5 m, 50 m and 100 m respectively.

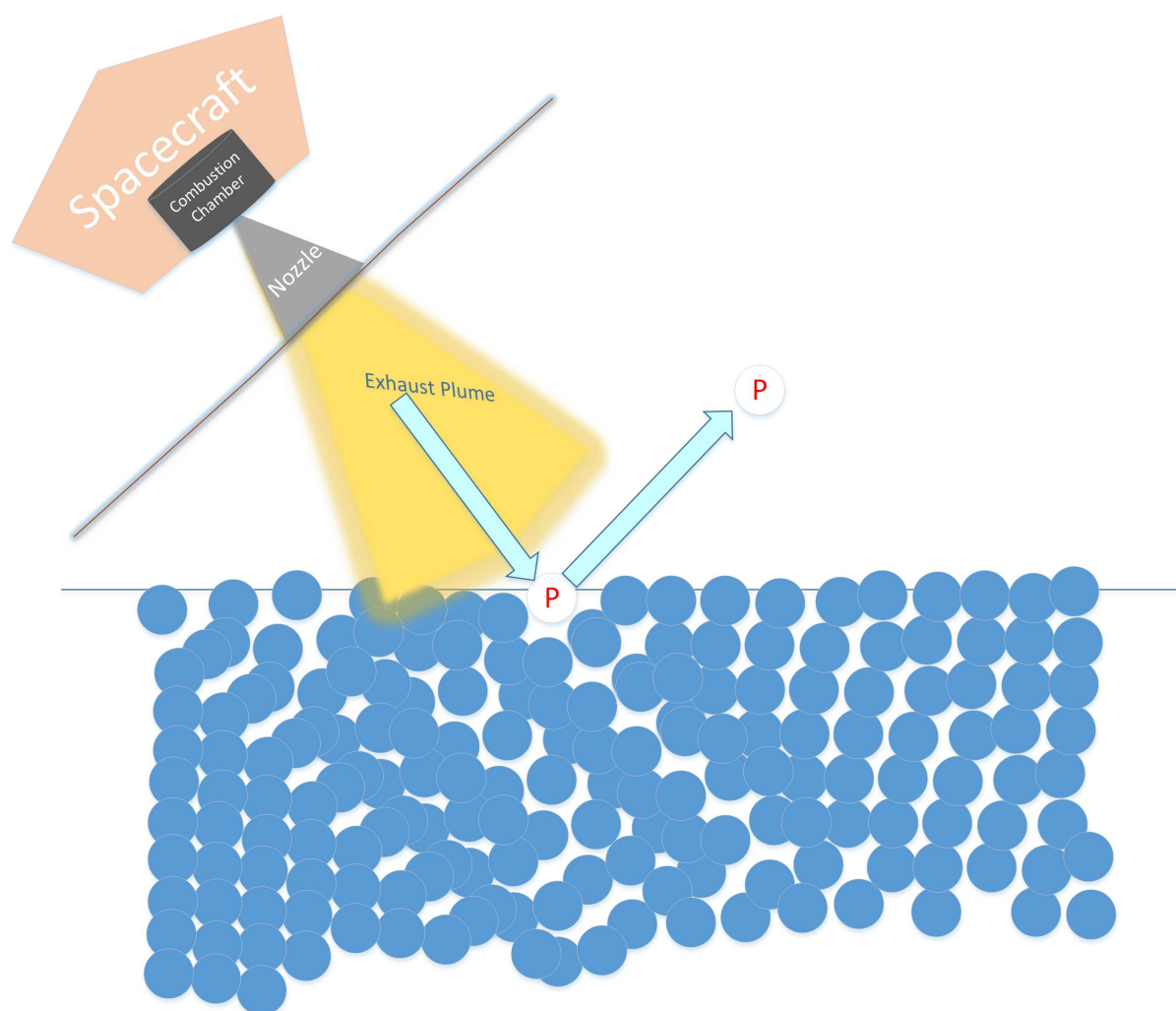
Figure 5: Volume of the pit formed as a function of hardness of the surface for impinging particles of varying velocities. Altitude of the lander is fixed at 5m and hovering duration is 30 s.

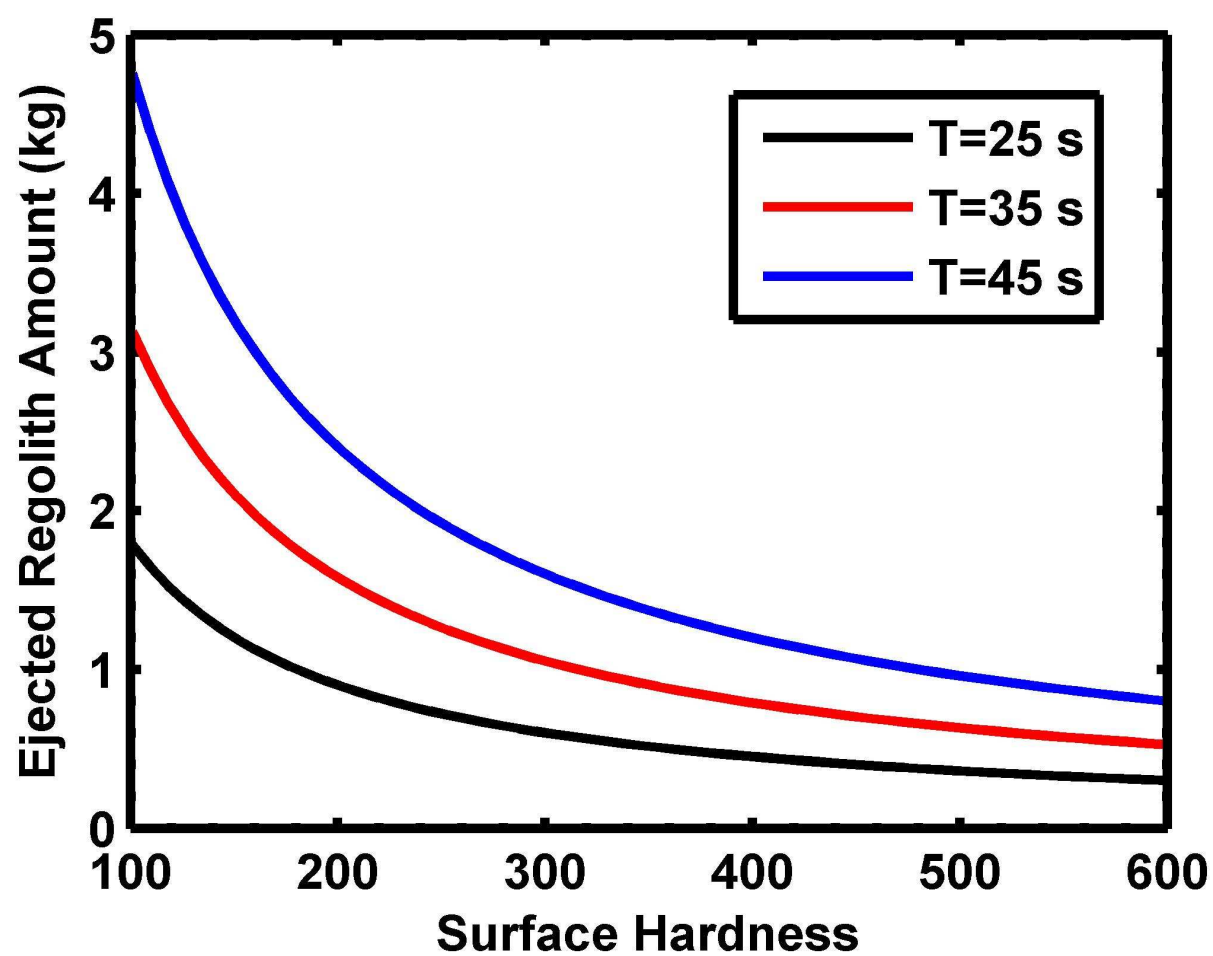
Figure 6: Variation of mass flux rate with grain size for particles of varying bulk density

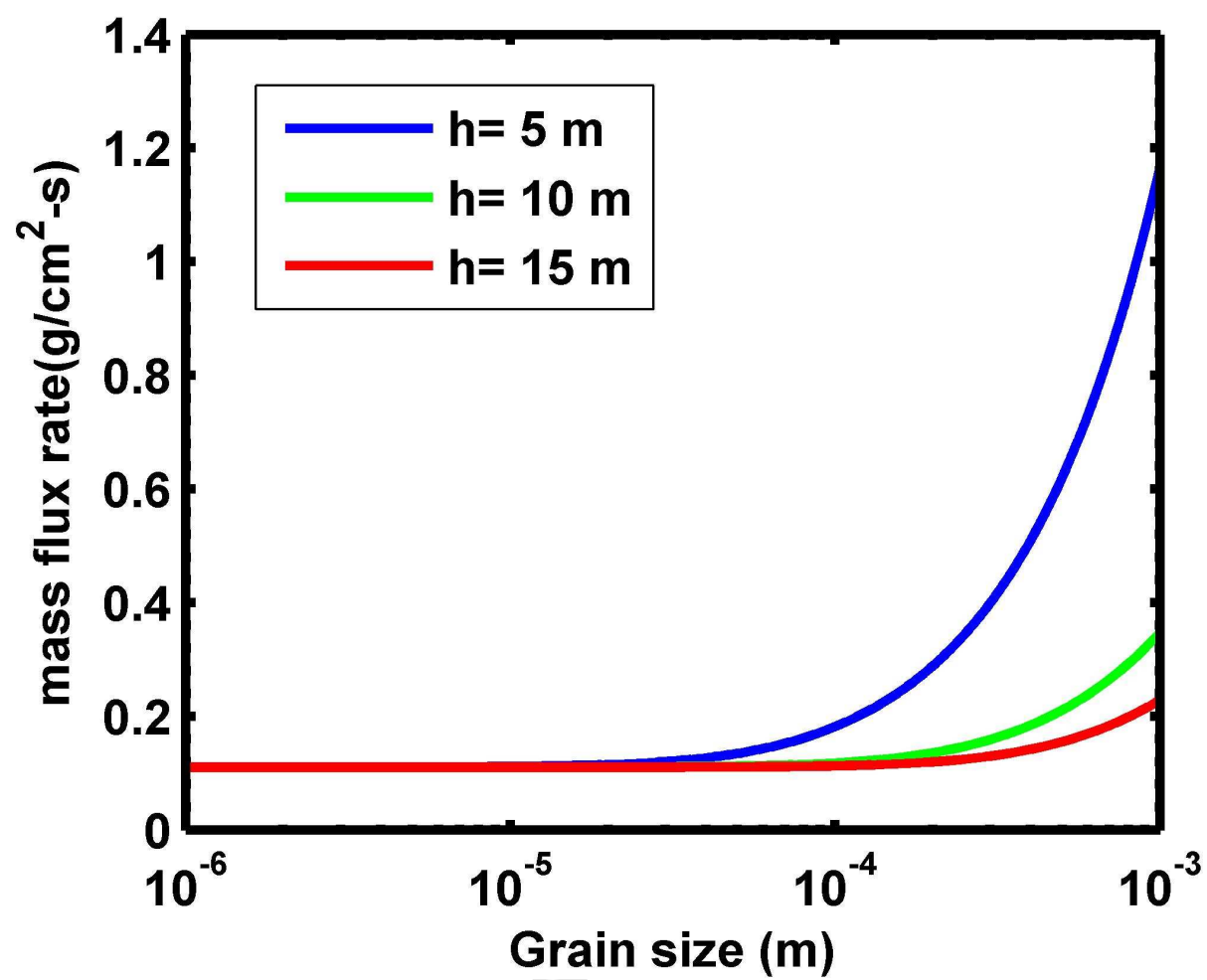
Figure 7: Illustration of eject particle kinematics and cratering formation during landing (not to scale. For representation purpose only).

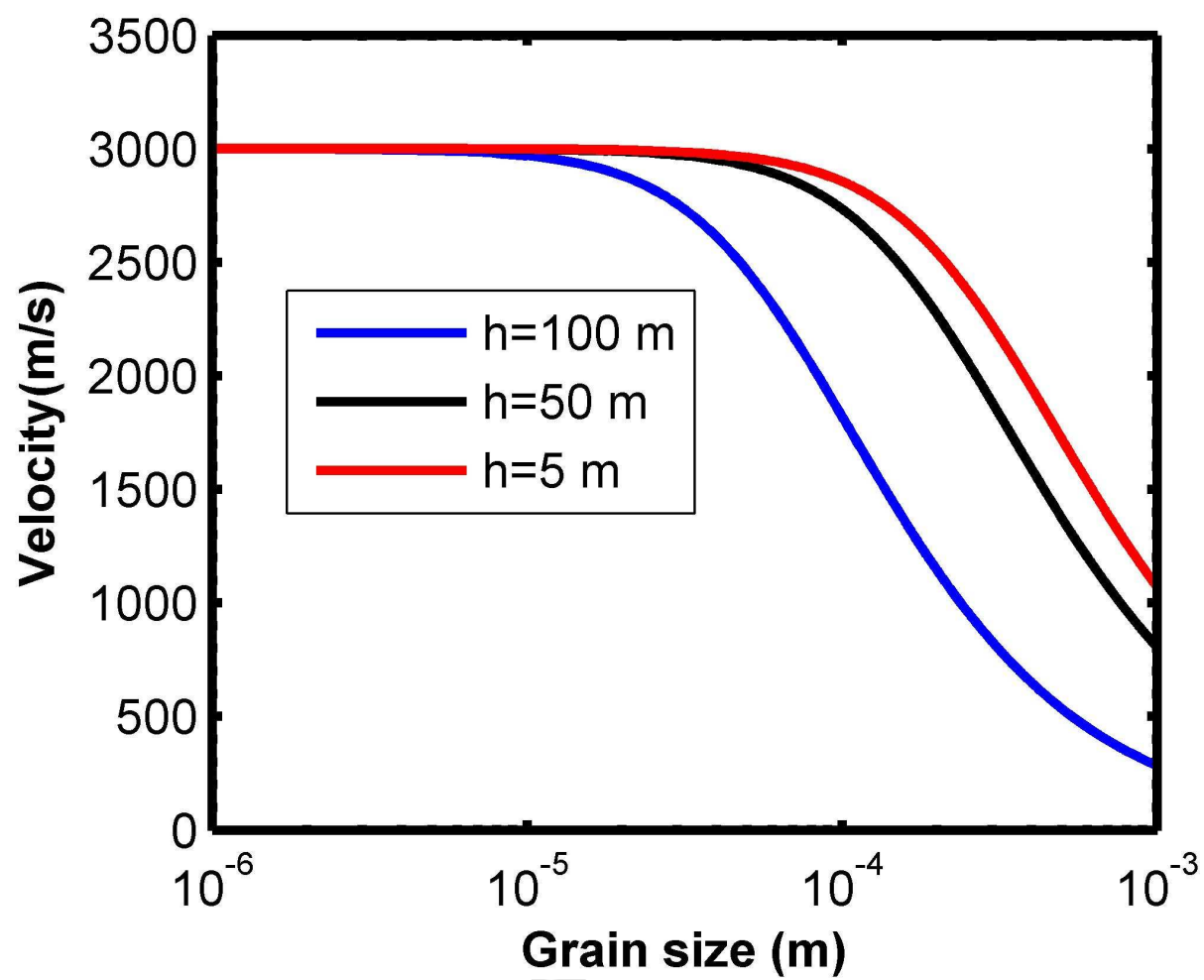
Parameter	Value
Dust particle diameter (D)	1-1000 microns
Engine thrust (F)	800 N
Dust particle density (σ)	1500 kg/ m ³
Combustion chamber viscosity (μ_c)	10 ⁻⁴ poise
Combustion chamber temperature (T _c)	3031 K
Mach number at exit plane	5.44
Drag coefficient (C _d)	2.0
Cohesive stress of soil (c)	96 Pa
Diameter of the nozzle (d)	29.4 cm
Friction angle of the soil (ϕ)	35 ⁰
Shear stress caused by the plume at the boundary layer (τ)	10000 Pa
Exit plane gas velocity (u)	3000 m/s
Hovering Altitude (h)	5m
Hovering Duration (t)	30 s

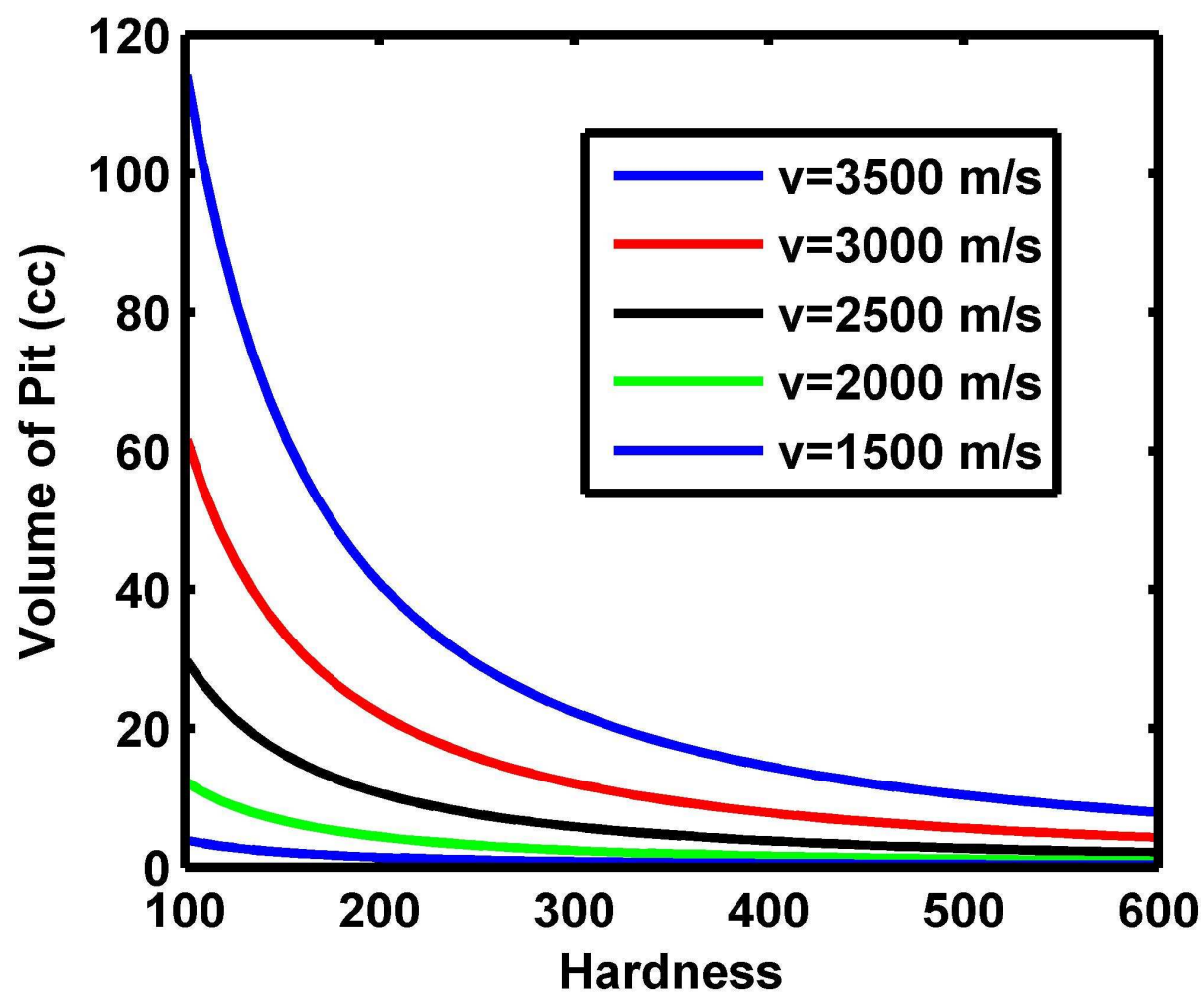
Case	Parameter	Value 1	Value 2	Value 3
1.	Soil Bulk Density	1.5 g/cc	1 g/cc	0.5 g/cc
2.	Hovering Duration	55 seconds	35 seconds	15 seconds
3.	Jet Plume Velocity	3500 m/s	2500 m/s	1500 m/s
4.	Hovering Altitude	15 m	10 m	5 m

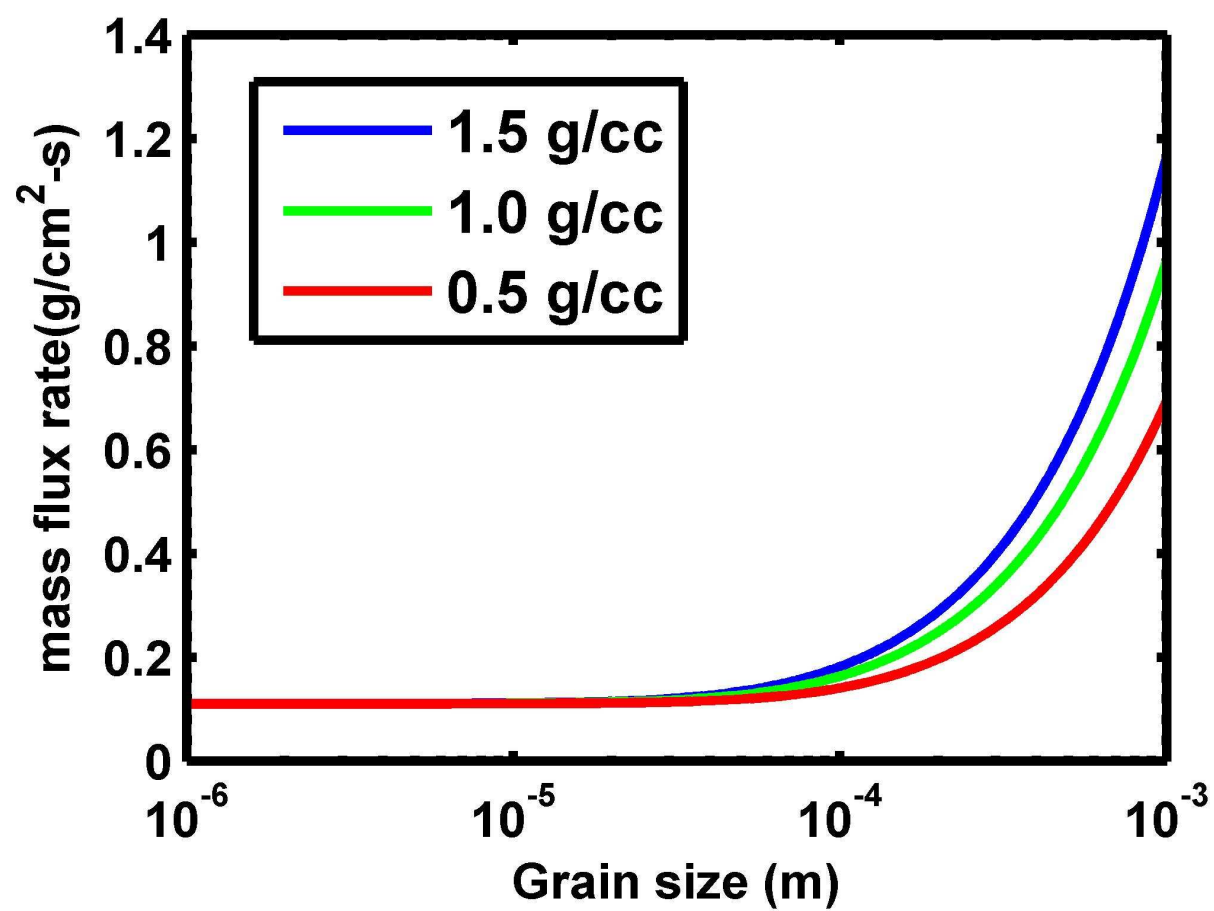


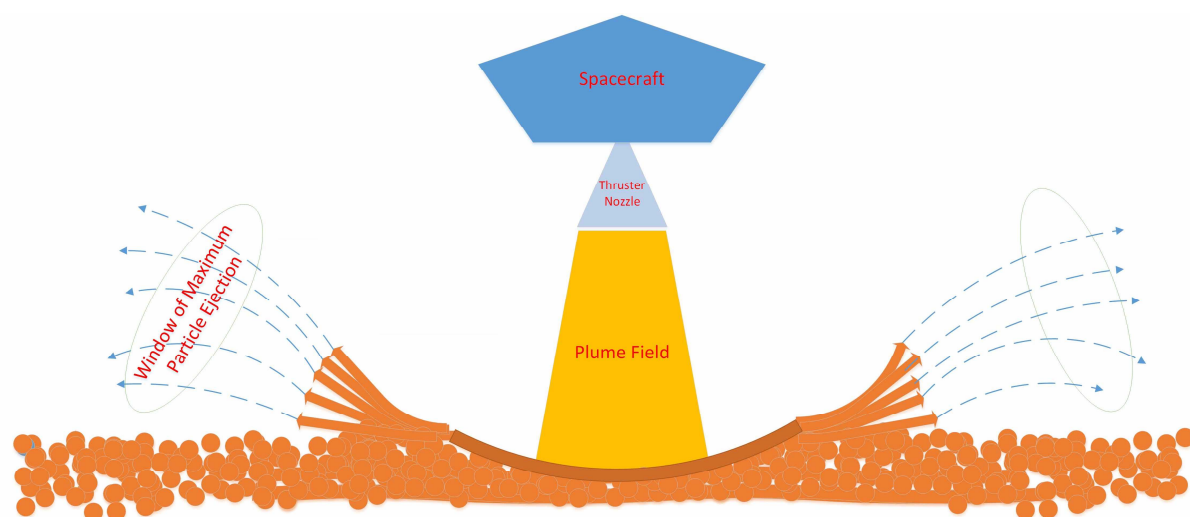












Highlights

- Methodology developed for numerical evaluation of disturbance at landing site for lunar landings.
- Variability of eject velocity with hovering time and altitude was carried out.
- Variability of mass flux rate with hovering height and duration was carried out.
- Variability of total ejected volume with grain size and density was carried out.
- Kinematics of ejected dust particle was also carried out and results are presented.